General Approach to Seismic Stability Analysis of Earth Embankment Dams

**Donald H. Babbitt, P.E.[1] and
Stephen W. Verigin, P.E.[2]**

Introduction

The State of California is one of the most seismically active regions in the world. Micro-seismic earthquakes occur daily and major earthquakes, with the potential of threatening life and property occur frequently. In the last decade over 100 residents lost their lives during the Loma Prieta and Northridge earthquakes in October, 1989 and January 1994 respectively. Most of the fatalities resulted from bridge and building failures. Significant structural damage was incurred at a number of dams (Refs. 2 and 16), but there were no failures in either event.

The most well-known earthquake damage to an embankment dam in California occurred during the 1971 San Fernando earthquake. Both Upper San Fernando and Lower San Fernando dams, hydraulic fill embankments, were severely damaged. Lower San Fernando Dam came within 5 feet of being breached when the upstream slope slid into the reservoir and the crest settled 30 feet, (Ref. 11). Much of the original research and many recent advances in seismic embankment stability analysis are based on observations, collected data, and back calculations of the performance of the San Fernando dams.

The California Department of Water Resources, Division of Safety of Dams (DSOD) began reanalyzing embankment dams following the San Fernando earthquake. Over 100 dams have been reanalyzed. There have been 60 dams physically modified, 19 are operating under permanent storage restriction, 36 have operated under preliminary restriction pending plans to mitigate deficiencies, and 4 have been removed from service (Ref. 1) as shown in Table 1.

The DSOD approach to analyzing earth embankment dams and their foundations has evolved since 1971 following the state-of-practice in the profession. Technological advancements have made computer solutions more attainable but recent trends have been toward simpler solutions. Much of the problem with analyzing embankments is our inability to representatively sample and test earth materials, understand the behavior of observed performance, and conceptualize and model failure modes for the multitude of different embankment sections.

---

[1]Chief, Design Engineering Branch, California Division of Safety of Dams
[2]Supervising Engineer, California Division of Safety of Dams

TABLE 1 - IMPROVEMENTS TO DAMS

Berms added or slopes flattened	19
Freeboard increased by adding embankment	3
Freeboard increased by lowering spillway	15
Crack Stopping zones added	6
Concrete dams structurally modified	10
Foundation grouting or drainage	8
Vibroflotation	1
Dams removed	4
Replacement dams constructed	9
Reservoirs maintained empty	7
Permanent storage restrictions	12
Temporary storage restrictions pending mitigation	36
Outlet works rehabilitations	3
Diversion conduits plugged	2
Total Improvements	132

Note: A single dam may have more than one improvement.

The purpose of this paper is to identify the many tools available to the practicing engineer, discuss how the tools are used within DSOD and outline the general steps for analyzing an earth embankment dam. The fact that no two embankment designs and settings are identical will be emphasized. The significance of this knowledge is that there is no one "correct way" for analyzing an embankment dam.

Exploration and Testing

The purpose of exploration and testing is to determine the physical characteristics of the foundation and embankment and their engineering properties. An understanding of the site geology is essential to gain insight for developing exploration and testing programs that will aid in the construction of analytical models. A geologist can assist the engineer in making judgements on the extent, homogeneity or lack there-of in a foundation. By understanding the process by which the foundation was formed, the engineer can gain confidence in the geotechnical model. The essential exploration and testing items are:

Exploration

- Surface Trenching - Trenching can reveal depth of soil and/or degree of rock weathering, and the characteristics and variability of near-surface foundation. Trenching is also valuable for investigating fault and prominent jointing features.

- Drilling - Material identification and geotechnical engineering properties of subsurface geologic units are determined from drilling. The objective of a well designed drilling program is to confirm the at-depth foundation profile including discontinuities. It is important to remember that a drillhole represents an extremely small percentage of the foundation area or volume of the dam. A sufficient number of samples must be obtained and tests performed to produce confidence in the interpolation between drillholes.

- Standard Penetration Testing (SPT) - This test which is routinely done as part of the drilling program is the most popular and oldest in-place test. It is most commonly used to indirectly determine density and strength through measurement of sample driving resistance (blowcounts). The curves presently used by DSOD are shown in, Figure 1.

- Cone Penetrometer Tests (CPT) - The CPT is often proposed when a large number of tests are desired. It is a cheaper test than the SPT, and provides a continuous log of the hole. The CPT is useful for reconnaissance level investigation or for defining the extent and depth of known soil or rock units over large areas. It is not considered as dependable as the SPT for material identification and liquefaction evaluation by DSOD because no samples are retrieved. When CPT data is used for liquefaction analysis, DSOD requires a minimum of two SPT companion holes for establishing a site specific correlation.

- Becker Hammer Testing - This test has been used on several projects reviewed by DSOD for analyzing liquefaction potential of gravelly soils. Results have been mixed. In some cases the Becker values have been consistent with the available limited site SPT results. On other projects Becker values have not agreed with SPT blowcounts and have not been consistent or meaningful from one hole to the next on the same job. The test method is not disallowed but is not considered reliable enough to be used as a singular investigative technique.

- Seismic Surveys - Seismic survey data is considered valuable for reconnaissance level geologic and geotechnical site evaluation. Data gathered from these methods would not be used for direct assignment of soil strength for seismic stability analysis, (the exception to this is that the cross-hole shear wave velocity test is considered the best method available for determining shear modulus).

Laboratory Testing

The primary objective of laboratory testing soil for embankment stability analyses is to determine shear strength. Many methods of shear strength testing have been used over the years and are appropriate when the selected testing method matches actual field conditions and critical failure mode. One of the greatest challenges in shear strength testing remains obtaining representative samples. Inplace testing (SPT, CPT and Becker) is often done to determine liquefaction potential and residual strength for stability analyses because sampling and shear strength testing is so difficult. Questions have also been raised (Ref. 9) as to how well shear strength testing models the loss-of-strength phenomenon of soils subjected to seismic loading (See Fig. 3).

- Direct Shear Test - Is appropriate for low embankments that will probably not be subject to significant pore-pressure build-up in undrained loading conditions. Uncertainty exists for distinguishing drained from undrained strengths for partially saturated soil samples. Direct shear testing may be sufficient when the seismic stability margin of safety is large.

- Monotonic Triaxial Shear Tests - Can provide an understanding of the drained and undrained soil strengths sheared under constant load. Dilative or contractive behavior of the sample can be judged by examining the porewater pressure behavior during shearing. Limitations to this type of testing are that it does not simulate cyclic loading, sample disturbance may significantly affect test performance, and non-representative strengths may be assigned if too few samples are tested.

Testing undisturbed samples has been advocated (Ref. 8) as the best means for determining steady-state or residual strength. In DSOD's limited exposure, we have observed a lack of consistency between shear strength determined by testing undisturbed samples compared to those predicted by charts correlated to SPT blowcounts. The methodology is analytically sound but to date is viewed as data to be considered in addition to all other data.

- Cyclic-Triaxial Shear Tests - Once the most popular test for predicting "cyclic-strength", this test is seldom used for analyzing existing dams. Sampling difficulty and duplication of failure mode are unresolved problems associated with this test. It is occasionally still used to predict cyclic strengths for major new construction projects. Results are looked on with more confidence for new dams than existing dams because samples can be prepared to design specifications. Testing of coarse materials is not practical because of required sample size and equipment limitations. Results of tests on scalped gradations must extrapolated to approximate strengths.

- Soil Classification Tests - Aid the engineer in relating his/her experience and knowledge of soil type to expected behavior under seismic loading. For example, if it is known that a low dam is constructed of a medium-high to high density clayey soil, the engineer can initially assess there is little likelihood there will be significant porewater pressure increase and resulting loss of shear strength under seismic loading. Likewise, knowing that a soil is a non-plastic silt or cobbly loose alluvium will give the engineer insight into probable soil behavior and appropriate exploration, testing, and analytical techniques for use in further evaluation.

- Moisture - Density - Results from these tests are directly and indirectly used to judge the general quality of an embankment and foundation (See Fig. 4). Experience has shown that low density soils (such as hydraulic fill embankments or loose alluvial foundations) are extremely contractive, have very low undrained strengths and are susceptible to large deformations. Dense earthfill dams (usually rolled earth construction, using good materials, built in the past 30 to 40 years) have correspondingly higher shear strengths and will not flow as a liquefied mass although they can incur deformation if violently loaded.

Analysis

DSOD reviews both analyses prepared by or for dam owners and makes independent analyses. Independent seismic stability evaluations of embankment dams are presently done using simplified techniques on desktop computers. Limit equilibrium stability analyses, the Seed and Idriss approach to liquefaction potential based on blowcounts, Newmark type deformation calculations, and Makdisi-Seed deformation evaluations are considered simplified, whereas, analysis by finite element and finite difference computer modeling is considered rigorous.

Approaches to liquefaction potential, residual strength determination, and deformation computations are abundant. Many hybrid approaches to the procedures documented in literature have been proposed for DSOD review and approval over the years. The approaches generally have been formulated logically and combine the work of many researchers, but have not been substantiated by observed performance of existing dams and must therefore be viewed with conservative skepticism.

Rigorous finite element and finite difference approaches to analyzing seismic response of embankment dams are being considered for use by DSOD. The analytical results must be reviewed in detail because there have been few opportunities for calibrating computer models using actual dam performance. It is unlikely that DSOD will ever endorse a single embankment modeling software at the exclusion of others.

Seed - Idriss Liquefaction Potential Analysis

This empirical approach has been used for approximately 25 years to evaluate liquefaction potential in soil. It has been widely used on many projects by DSOD engineers to evaluate both embankments and foundations. As mentioned previously, CPT and Becker Hammer data is used in addition to the traditional and more commonly used SPT blowcounts. The method is well liked because it is simple, relies on no undisturbed sampling or laboratory testing, and has a large body of field data to support the ensuing computations. The major drawback is the number of correction factors that must be applied to raw blowcount data before liquefaction computations can be made. Correction factors can cumulatively change field blowcounts by as much as 100 percent. While all correction factors have been logically devised, there is no certainty they are all quantitatively valid.

Residual Strength

Residual strength of liquefied soil masses is typically assigned using corrected SPT blowcounts and the Seed-Harder curves (Ref. 15 and Fig. 2). Steady-state strengths, as proposed by Poulos and Castro (Ref. 8) are considered theoretically sound by DSOD and would also be considered for stability and deformation analyses. As noted by others (Ref. 7) obtaining steady-state strengths can be expensive and difficult but that does not prevent DSOD from approving an owners plan for using the approach.

Stability Analyses

Pseudo-Static-Analysis is done routinely as a traditional approach for comparison with other dams. Yield accelerations are calculated, for possible future deformation calculations. No effort has been made by DSOD to associate pseudo-static coefficients with a design earthquake. The factor of 0.15 a/g is typically used with a required minimum factor of safety of 1.10. Undrained strengths are used where they are less than drained strengths. Low undrained strength envelopes are considered indicative of soils subject to strength loss during shaking. DSOD seismic stability evaluations never end solely on the basis of satisfactory pseudo-static factors of safety.

Post-Seismic Limit Equilibrium computations are made to predict that a dam is stable (factor of safety greater than unity) or unstable (factor of safety less than unity) following the earthquake. If the post seismic factor of safety using residual strengths is less than unity, the dam is considered unstable and major reservoir operating restrictions or embankment modifications are required. If the embankment is found stable the analysis proceeds to an evaluation of the potential deformation that will result from seismic loading. It is possible that an embankment will be found stable (factor of safety greater than unity) but judged deficient with respect to safety because calculated deformations are too large.

Deformation Analysis

Newmark Sliding Block - Analyses have been used in varying approaches by DSOD. The simplest approach is where no embankment response with respect to structural period is required. This would be for a low-period embankment (low height). For dams up to 150-feet DSOD has made deformation analyses using the Makdisi-Seed simplified approach. The deformation charts are not considered applicable to structures of greater height because they were not included when the authors formulated the methodology. Also accepted in the past by DSOD is an approach where the embankment response is calculated using finite element analysis and then deformations calculated using the embankment response time history input to sliding block computations (roughly, the approach used by Makdisi and Seed to devise their deformation charts).

Conservative judgement is exercised by DSOD in reviewing all deformation analyses including those done in-house. Deformations of 0 to 5 feet are considered sustainable provided the deformation is not too large a percentage of the total dam height and do not seriously compromise freeboard. A 0 to 5 foot deformation computation on a large dam could actually be a prediction of nothing more than structural cracking under heavy seismic loading. Computations will almost always predict some deformation if a dam is subject to peak ground accelerations exceeding about 0.35g.

Deformations of 5 to 10 feet are considered serious. As the number approaches ten feet DSOD does not believe all related structural behavior is predictable. Transverse cracking, especially at the abutments, is one concern that has been observed but not effectively calculated. Other types of embankment cracking and local slumping are also deemed possible. Freeboard, crest-width, zoning, remaining freeboard, and embankment slopes would all be considered before final decisions on whether a 5 to 10 foot deformation is acceptable without structural modifications.

Deformations greater than ten feet are considered to be in nearly the same class as embankments with post-seismic factors of safety less than unity. DSOD does not consider that there is precedent for predicting the final configuration or embankment integrity for dams sustaining deformations in excess of ten feet. Structural modifications will in all likelihood be required.

Procedure for Analyzing Seismic Stability

1. Develop design seismicity, a maximum credible earthquake (MCE) is required by DSOD.

2. Design an exploration and testing program consistent with seismic loading, site geology, dam size, and existing data. Minimum level of exploration and testing should be:

   Exploration

   - Site inspection by geologist and geotechnical engineer.
   - Trenching.
   - Continuously sampled and logged drillholes with SPT's taken at a maximum of five-foot intervals. (Number and depth depending on dam size and site conditions).

   Testing

   - Soils classification tests.
   - Determination of In-place densities.
   - Moisture - Density tests.
   - Shear strength tests (type is dependent on projected need for analysis).

3. Perform preliminary analysis of embankment and foundation to identify need for further analysis. Liquefaction potential analysis is done at this point to determine liquefiable, soil units, and assign preliminary residual strengths. Preliminary stability analyses are performed and a decision is made that the dam is either stable or further evaluation is required.

4. Design plan for second phase exploration and testing program. Items that will potentially cause stability problems have now been identified and program is designed to concentrate on those items. A method of analysis considered most appropriate for evaluating the dam stability is selected. It is important to gather all data necessary to perform the analysis. Exploration and laboratory tests that are usually considered at this point are:
   - Additional borings and SPT testing.

- CPT testing.
- Becker Hammer testing.
- Seismic Surveys.
- Undisturbed sampling for triaxial shear testing.
- A specific shear test required to perform the desired analysis.

5. Perform stability analysis. If dam is unstable proceed to conceptual repair design. If dam is stable evaluate potential deformations.

6. Perform deformation analysis. Simplistic or rigorous approach may be selected depending on anticipated deformation magnitudes, size and potential hazard posed by deformations, and applicability of dam characteristics to selected model.

7. Evaluate deformation results and determine need for additional work required to assure that dam failure will not occur under design seismic loading.

Conclusions

Performance of embankment dams during California earthquakes has generally been satisfactory. The reaction to the 1971 San Fernando Earthquake was certainly prudent. If several older dams had not been taken out of service or modified, they probably would not have survived subsequent earthquakes.

The techniques we have for predicting earthquake performance are not simple. They require the use of adjustment factors and reliance on standard properties determined by researchers. Exact answers are not produced. This is troubling, but not much different than using hydrology to determine spillway design flows, published weir coefficients, and Manning's "n" values to determine basic spill geometry and then adjusting "by judgement" to consider crosswaves and bulking.

References

1. Babbitt, D. H., "Improving Seismic Safety of Dams in California", Geotechnical Practice in Dam Rehabilitation, Geotechnical Special Publication No. 35, ASCE, April 1993.

2. Bureau, G., et. al., "Effects on Dams of the Loma Prieta Earthquake of October 17, 1989", USCOLD Newsletter, November 1989.

3. Castro, G., Poulos, S. J., and Leathers, F. D., "Re-Examination of Slide of Lower San Fernando Dam", ASCE, Journal of Geotechnical Engineering, Vol. 111, No. 9, September 1985.

4. Davis, A. P., Broderick, W., and Castro, G., "Hinkley Dam Liquefaction Assessment and Remediation", Proceedings of Fourteenth Annual USCOLD. Phoenix, Arizona, June 1994.

5. De Alba, P., Seed, H. B., Retamal, E., and Seed, R. B., "Residual Strength of Sand from Dam Failures in the Chilean Earthquake of March 3, 1985", EERC, Report No. UCB/EERC - 87/1 1, September 1987.

6. Makdisi, F. I., and Seed, H. B., "Simplified Procedure for Estimating Dam and Embankment Earthquake - Induced Deformations", Journal of the Geotechnical Engineering Division, ASCE, Vol. 104, No. GT7, July 1978.

7. Marcuson 111, W. F., Hynes, M. E., and Franklin, A. G., "Evaluation and Use of Residual Strength in Seismic Safety Analysis of Embankments", Earthquake Spectra, Vol. 6, No. 3, 1990.

8. Poulos, S. J., Castro, G., and France, J. W., "Liquefaction Evaluation Procedure", ASCE, Journal of Geotechnical Engineering, Vol. 111, No. 6, June 1985.

9. Seed, H. B., "Design Problems in Soil Liquefaction", Journal of Geotechnical Engineering, ASCE, Vol. 113, No. 8, August 1987.

10. Seed, H. B., "The Rankine Lecture, 1979", Geotechnique 29, No. 3, 215-263, 1979.

11. Seed, H. B., et. al., "The Slides in the San Fernando Dams During the Earthquake of February 9, 1971", Journal of Geotechnical Engineering Division, ASCE, Vol. 101, No. GT7, July 1975.

12. Seed, H. B., and ldriss, 1. M., "Simplified Procedure for Evaluating Soil Liquefaction Potential", Journal of the Soil Mechanics and Foundations Division,

ASCE, Vol. 97, No. SM9, September 1971.

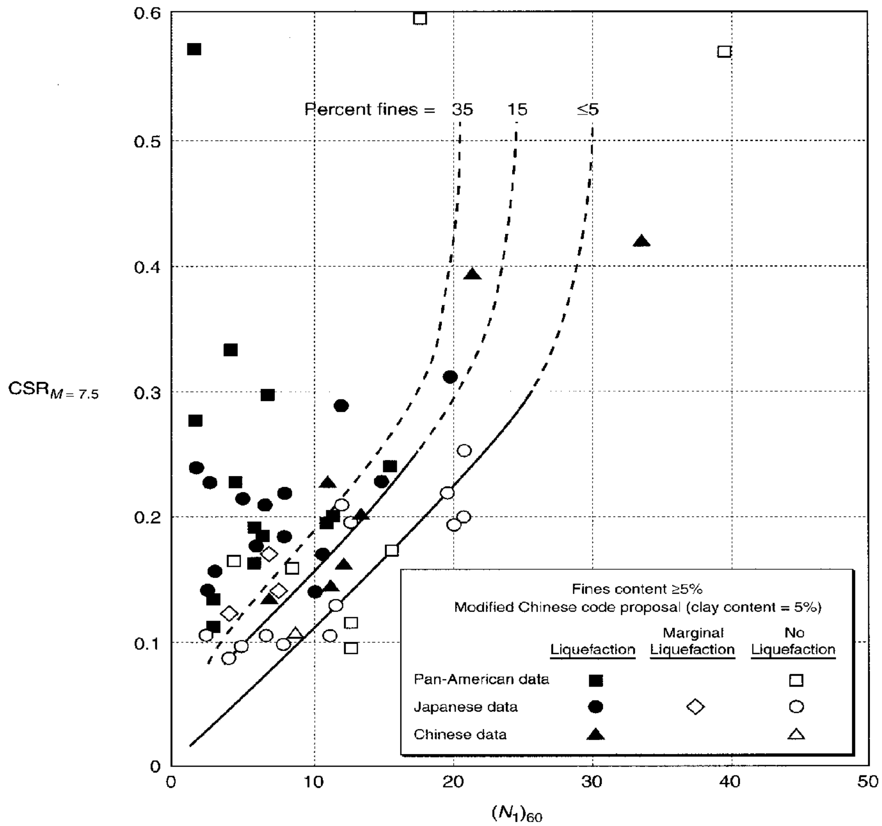
13. Seed, H. B., Seed, R. B., Harder, L. F., and Hsing-Lian, J., "Re-evaluation of the Slide in the Lower San Fernando Dam in the Earthquake of Feb. 9, 1971", EERC, Report No. UCB/EERC - 88/04, April 1988.

14. Seed, H. B., Tokimatsu L. F., Harder, L. F., and Chung, R. M., "Influence of SPT Procedures in Soil Liquefaction Resistance Evaluations", ASCE, Journal of Geotechnical Engineering, Vol. 111, No. 12, December 1985.

15. Seed, R. B., and Harder, L. F. , "SPT - Based Analysis of Cyclic Pore Pressure Generation and Undrained Residual Strength", H. Bolton Seed Memorial Symposium Proceedings, Vol. 2, May 1990.

16. Seismic Safety Commission, State of California, "Northridge Earthquake, Turning Loss to Gain", SSC Report No. 95-01, 1995.

17. USBR, "Design Standards, Embankment Dam's, No. 13", Chapter 13, Seismic Design and Analysis, December 1989.



Relationship Between Cyclic Stress Ratio Causing Liquefaction and N_1-Values for M=7½ Earthquake.

Recommended “Standardized SPT Equipment and Procedures

Sampler: Std. Sampler with: (a) O.D. = 2.00 inches, and (b) I.D. = 1.375 inches (constant - i.e. no room for liners in the barrel.)

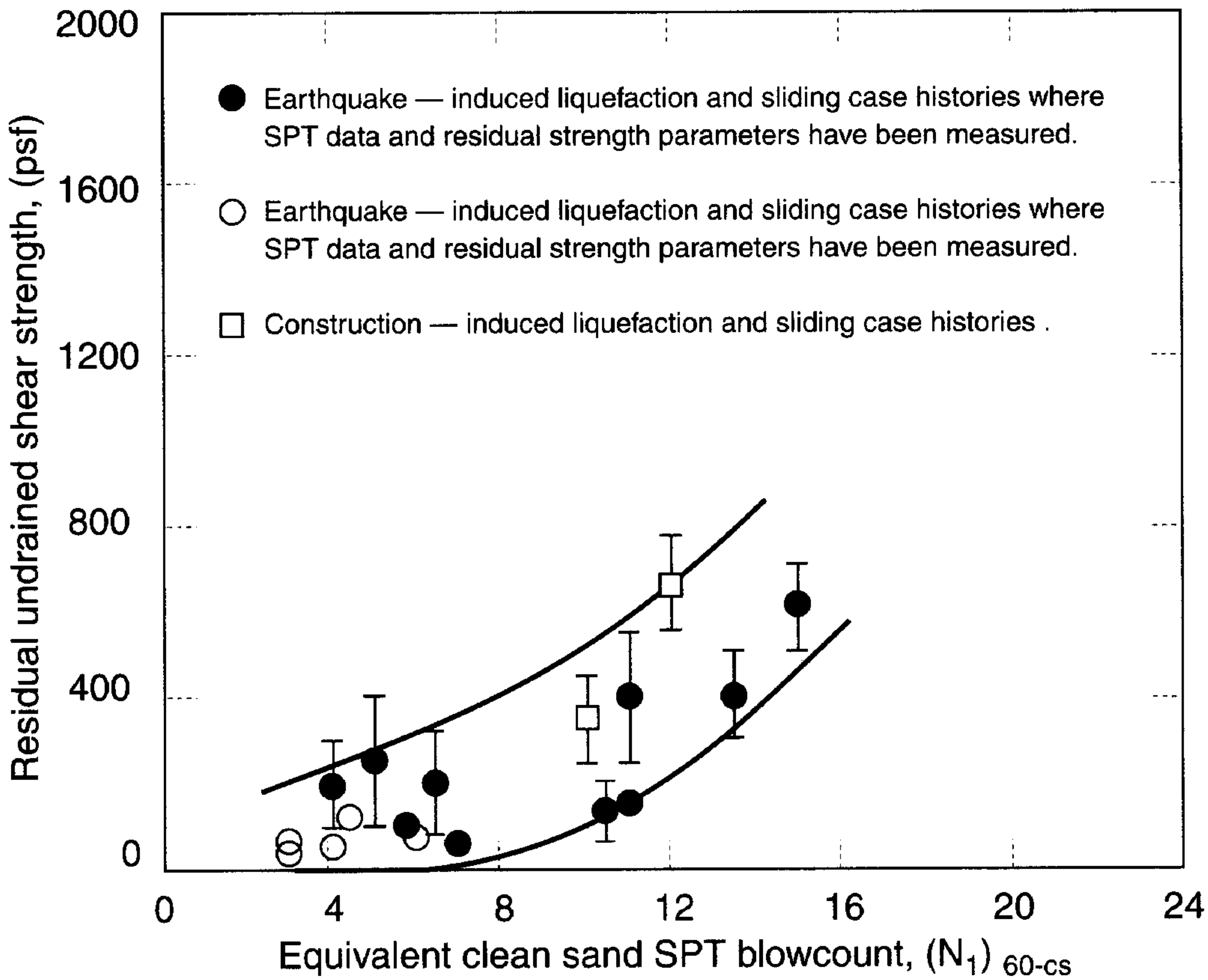
Drill Rods: A or AW for depths less than 50 feet
N or NW for greater depths

Energy Delivered to Sampler: 2520 in.-lbs. (60% of theoretical free fall maximum)

Blowcount Rate: 30 to 40 plows per minute

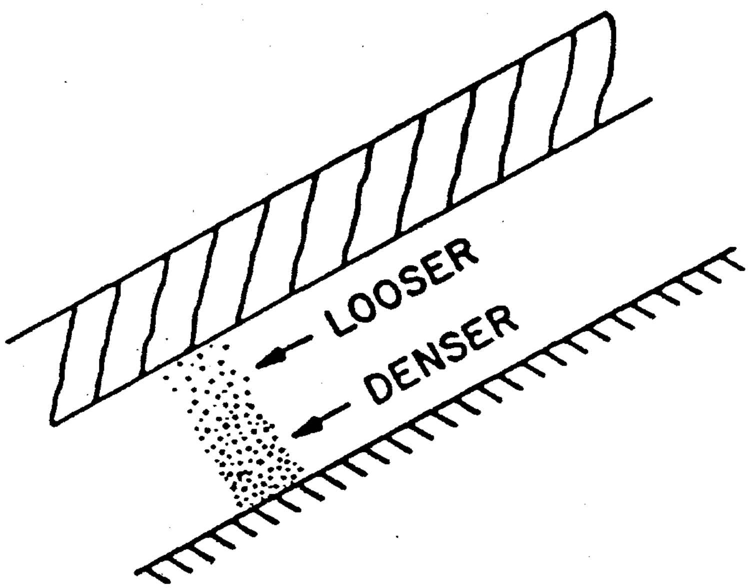
Penetration Resistance Count: Measured over range of 6 to 18 inches of penetration into the ground

Figure 1 - (After Seed, et al., 1984)



Relationship between corrected "Clean Sand" Blowcount $(N_1)_{60\text{-}CS}$ and Undrained Residual Strength (S_r) from Case Studies

Figure 2 - (After Seed and Harder)



Example of Potential Situation for Mechanism B Failure Arising from Rearrangement of Soil into Looser and Denser Zones

Figure 3 - (After Seed)

Guidelines

Combining the four categories of soil type, density, acceleration, and behavior results in the following general guidelines:

Acceleration

	Low 0 - 0.2	Medium 0.21 - 0.39	High 0.40+
Loose	1	2	4
Medium Dense		3	5
Dense			6
Very Dense		7	

Zones 1,3, & 6 — Borderline Zones - Cases that fall in these zones may or may not present a problem. A small investigative program is desirable to determine if there is a problem. Group III soils (clayey) might experience 0 - 5 percent settlement. There is some possibility for liquefaction of Groups I and II soils.

Zones 2 & 5 — Problem Zones - Cases that fall in these zones will usually present some type of problem. An investigative program would be desirable. Settlement for Group III soils might range from 5 - 10 percent. Liquefaction for Groups I and II is very possible.

Zone 4 — Real Problem Zone - An investigative program should be initiated immediately. Settlement for Group III soils might range from 10 - 20 percent. Probability of liquefaction for soil Groups I and II is very high.

Zone 7 — No Problem - Cases that fall in this zone will normally not present any problems.

Figure 4 - (After DSOD)